POWER QUALITY IMPROVEMENT USING DYNAMIC VOLTAGE RESTORER (DVR)

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POWER QUALITY IMPROVEMENT USING DVR

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By

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May 2015

Dedicated to

My

Professor

NATIONAL INSTITUTE OF TECHNOLOGY

ROURKELA

CERTIFICATE

This is to certify that the thesis entitled, **"Power quality improvement using DVR"** submitted by **Dev Kumar Taram (Roll No. 213EE5354)** in partial fulfilment of the requirements for the award of Master of Technology Degree in Electrical Engineering with specialization in Industrial Electronics during 2014 -2015 at the National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

Place: NIT Rourkela

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DECLARATION

I hereby declare that the investigation carried out in the thesis has been carried out by me. The work is original and has not been submitted earlier as a whole or in part for a degree/diploma at this or any other institute/University.

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Contents

CHAPTER 4

SIMULATION RESULTS AND DISCUSSION

CHAPTER 5

CONCLUSION AND FUTURE SCOPE

ABSTRACT

Now a day power quality problem has become a major issue to deal with, in order to maintain quality supply. Modern generation greatly depends on electrical energy for improving their life style. Modern equipment like computers, electric motors etc. cannot run without electricity. In order to improve the performance, the equipment demands quality supply.

The power quality is affected by various factors of the electrical network. Power quality problems such as voltage and frequency variation, harmonic contents affect the performance of electrical utility and shorten its life time. Such problem has to be compensated to ensure the quality supply.

One of the most frequently occurring power quality problems in transmission network is voltage sag/swell. Such problems can cause heavy flow of current reduces the life time of the equipment or can cause over voltage affecting the insulation level of the equipment.

Many modern custom devices are present in order to mitigate such problems. Among them, Dynamic Voltage Restorer (DVR) is efficient and cost effective. In this paper, an overview of DVR and control scheme used to control the DVR is presented. The simulation result with the proposed control scheme is also shown.

List of Figures

List of Tables

List of Abbreviations

D-STATCOM	Distribution Static Compensator
DVR	Dynamic Voltage Restorer
UPQC	Unified Power Quality Conditioner
VSI	Voltage Source Inverter
SPWM	Sinusoidal Pulse Width Modulation
SVPWM	Space Vector Pulse Width Modulation
SVM	Space Vector Modulation
PQ	Power Quality
SLG	Single Line to Ground fault
PCC	Common Point of Coupling
HV	High Voltage
Pf	Power Factor
PLL	Phase Locked Loop
PWM	Pulse Width Modulation
FACTS	Flexible AC Transmission System

CHAPTER 1

1.1 Introduction

1.2 Literature review

1.3 Research motivation

1.4 Objective of the work

1.5 Organization of the Thesis

1.1 Introduction:

Electrical energy is the simple and well regulated form of energy, can be easily transformed to other forms. Along with its quality and continuity has to maintain for good economy. Power quality has become major concern for today's power industries and consumers. Power quality issues are caused by increasingly demand of electronic equipments and non-linear loads. Many disturbances associated with electrical power are voltage sag, voltage swell, voltage flicker and harmonic contents. This degrades the efficiency and shortens the life time of end user equipment. It also causes data and memory loss of electronic equipment like computer.

Due to complexity of power system network voltage sag/swell became the major power quality issue affecting the end consumers and industries. It occurs frequently and result in high losses. Voltage sag is due to sudden disconnection of load, fault in the system and voltage swell is due to single line to ground fault results in voltage rise of unfaulted phases. The continuity of power supply can be maintained by clearing the faults at faster rate. Other power quality issues i.e. voltage flickering, harmonics, transients etc has to be compensated to enhance the power quality.

Power electronic devices i.e. Distribution Static Compensator (D-STATCOM) and Dynamic Voltage Restorer (DVR) been recently used for voltage sag/swell compensation. In this project DVR is proposed which can protect the end-consumer load from any unbalance of voltage supply. It is a series compensating device, can maintain the load voltage profile even when the source side voltage is distorted.

1.2 Literature Review:

The electrical power supplied to the end consumer should be of high quality. Low power quality supply to the consumer adversely affects the performance of the equipment. Factors like voltage disturbance, frequency alternation and harmonic contents result in poor power quality of supply. Voltage variation is one of the most frequent disturbances occurring in the power system network. Such disturbance has to be compensated in order to maintain power quality.

Recently developed power electronic devices helps in mitigating such problem. Many custom devices such as DVR, D-STATCOM and Unified Power Quality Conditioner (UPQC) are proposed. Among them, DVR is the most effective device used for voltage disturbance problems. Hence, appears to be a better solution for current situation. DVR was firstly installed in North America in 1996, in Anderson at 12.47 KV substation. Since then, it is being used to protect the sensitive loads.

Design and study of DVR is presented in [1-5]. It gives an overview of DVR control scheme and its modelling. It shows that DVR provide efficient voltage restoration capability. The basic structure and the operating principle of DVR are shown. Different compensation technique of DVR is discussed.

Different control technique commonly used for Voltage Source Inverter (VSI) is presented in [6-10]. Different control scheme is shown and are discussed. The performance of various techniques are evaluated and compared.

The performance evaluation of DVR with Sinusoidal Pulse Width Modulation (SPWM) and Space Vector Pulse Width Modulation (SVPWM) is presented in [11-14]. Two PWM based control techniques are shown to control the VSI. SVPWM technique is compared with SPWM technique and shows that SVPWM has better DC utilisation and lesser harmonics are produced as compared SPWM.

Simulation of SVPWM and its application in three phase inverter is presented in [15-16]. The paper gives an idea of SVPWM algorithm and its simulation. The simulation result shows that SVPWM techniques are best suited for high power applications.

New scheme to control the two level VSI is presented in [17]. Detailed study of one of the SVPWM scheme i.e. seven segment space vector modulation (SVM) is done. Determination and realization of different switching states, sector value calculation, approximation of reference voltage vector and switching time calculation for linear modulation range is discussed.

SVPWM based DVR is presented in [18-22]. In this control algorithm in which the three phase supply, is converted into synchronously rotating d-q reference frame. The d-component gives information for depth of sag and q-component tells us about phase shift information. The error generated is given to SVPWM for DVR operation.

1.3 Research Motivation:

Power quality is a significant tool of an electrical power system network. Now a day's equipment are more sensitive to power quality. In power system there may be fluctuation in power quality at the sensitive load due to faults and switching operation of breakers. This disturbance may result in failure of the equipment. Recent development in power electronic devices helps us to mitigate such problem. In this project DVR is used to maintain the power quality. This device can compensate the voltage unbalances efficiently.

1.4 Objectives of the work:

For an economic operation of power system power quality should be maintained properly. Voltage sag/swell has been concerned as major power quality issue. The main objectives of this project are:-

1. Detection of voltage sag/swell in the power system network.
2. To mitigate the power quality issue using DVR and its behavioural study.
3. To select the best suitable control technique for DVR.
4. To control the device in order to obtain desired performance.

1.5 Organization of the thesis:

The whole thesis is organised in the following way:-

Chapter 1 is about the research motivation and motivation of the work. It also gives small introduction related to power quality and objective of the work.

Chapter 2 is about the power quality problems, its importance for consumers and industries, impact and problem faced to maintain power quality and ultimately its effect on consumer appliances and also to find some suitable compensating device.

Chapter 3 is about the custom device used to mitigate the power quality problem concerned. It gives a small introduction about DVR. It also gives brief discussion of the basic structure, principle and control algorithm of DVR.

Chapter 4 presents the MATLAB simulation result of DVR under various disturbances. The simulation result shows that the device work satisfactory.

Chapter 5 discussed about the conclusion, future scope of the work and references.

CHAPTER 2

POWER QUALITY

2.1 Introduction

2.3 Power quality

2.3 Importance of power quality

2.4 Power quality problems and issues

2.5 Summary

2.1 Introduction:

With the increasing use of non-linear loads and complexity of the network, the power system network faces challenges to deliver quality power to the consumers. Electric power been delivered is affected by many factors at the distribution network which has to be compensated to improve the quality and quantity of power been delivered. This chapter discuss about the power quality, its necessity, power quality issues and consequences.

2.2 Power Quality:

Power Quality concerns about the utility ability to provide uninterrupted power supply. The quality of electric power is characterized by parameters such as "continuity of supply, voltage magnitude variation, transients and harmonic contents in electrical signals". Synchronization of electrical quantities allows electrical systems to function properly and without failure or malfunction of an electric device.

2.3 Importance of Power Quality:

PQ expresses the degree of similarity of practical power supply with ideal power supply.

1. If PQ is good then any load connected to the electric network runs efficiently without decreasing its performance.
2. If PQ is poor then any load connected to the network leads either to the failure of the equipment or reduction in its lifetime and performance.

In order to prevent the consequences of poor PQ and to improve the utility performance the electric power are analysed to resolve the PQ issues in order to determine the efficient compensation technique.

2.4 Power Quality problems:

Poor PQ problems ultimately results in economic loss of the power system network. PQ mainly concerns to maintain voltage and current profile i.e. any deviation in these parameters can cause severe damage to the electrical utility and end consumers. An overview of many PQ problems along with their causes and consequences are presented.

2.4.1 Voltage sag/dip:

The voltage sag or dip can be stated as decrease in nominal voltage level by 10-90% for short duration for half cycle to one minute as shown in fig.2.1. Sometime, voltage sag last for long duration such prolonged low voltage profile referred as 'under-voltage'. Voltage sag is further divided in three categories: instantaneous, momentary and temporary sags respectively.

Voltage sag are mainly caused due to occurrence of faults in power system, overloading of the electrical network and starting current drawn by heavy electrical loads like motors and refrigerators.

Voltage sag in power system network results in failure of relays and contactor, dim light and fluctuating power.

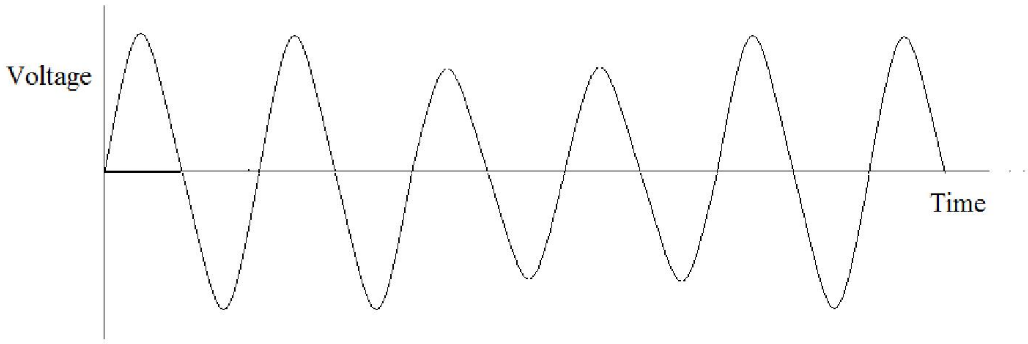

Fig.2.1 Voltage sag/dip

2.4.2 Voltage Swell:

Voltage swell can be stated as voltage rise by 10-80% of normal value for duration of half cycle to one minute as shown in fig.2.2. Likewise voltage sag, prolonged high voltage profile is referred as 'over-voltage'. Voltage swell is subdivided as:

i. Instantaneous swell
ii. Momentary swell
iii. Temporary swell

Voltage swell is mainly caused by disconnection of large load, Single Line to Ground fault (SLG) results in voltage rise in unfaulted phases and loose connection of neutral wire.

Voltage swells results in breakdown of insulation, overheating of electrical equipment and damage to electronic equipment.

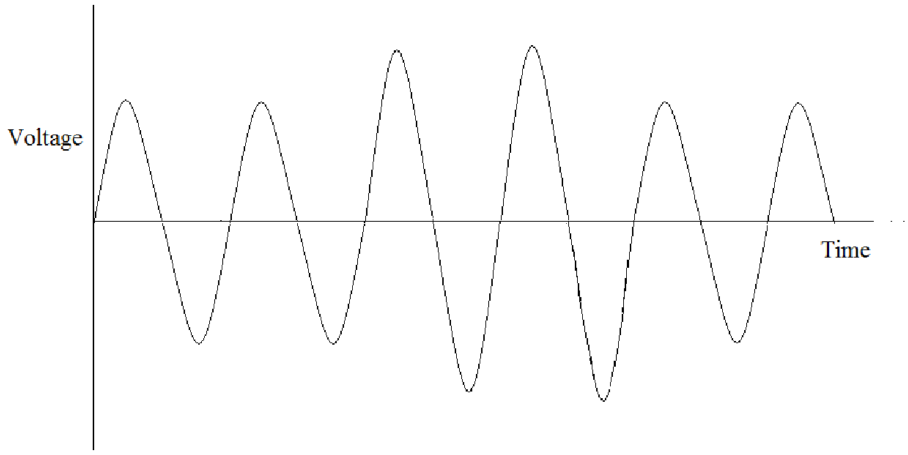

Fig.2.2 Voltage Swell

2.4.3 <u>Voltage Interruption</u>:

Voltage interruption can be stated as reduction in rms voltage by below 0.1 pu of nominal or complete failure of supply voltage. It can be further divided into two classes based on interruption time period:

1. **<u>Short interruption</u>:**

   If the interruption duration occurs for few milli-seconds then it is termed as short interruption. This is due to malfunctioning of switching devices which may affect the data stored in sensitive devices like PLCs.

2. **<u>Long interruption</u>:**

   If the interruption duration occurs for range between few milli-seconds to several seconds then it is termed as long interruption as shown in fig.2.3.

The main cause is disconnection of electrical power system for maintenance and faults in electrical network which may result in complete stoppage of supply.

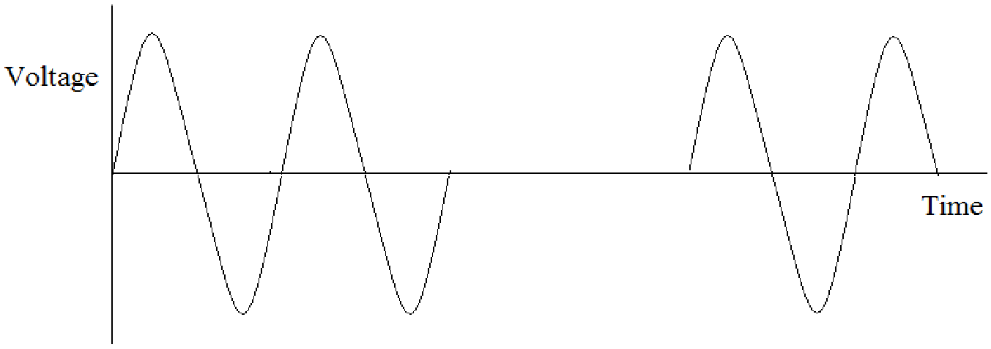

Fig.2.3 Voltage signal with long interruption

2.4.4 Waveform distortion:

Distortion means change in original waveform shape as shown in fig.2.4. In a power system network, the voltage and current waveform should be sinusoidal in nature. Waveform distortions are due to:

1. **Harmonics**:

   A harmonic is an integral multiple of fundamental frequency of electrical quantities. This is due to presence of non-linear loads which results in overheating of electrical equipment. Hence its reduction is desirable.

2. **Noise**:

   Any unwanted signals that results in fluctuation of voltage and current signals is termed as noise. Noise is due to communication line running in parallel with power lines.

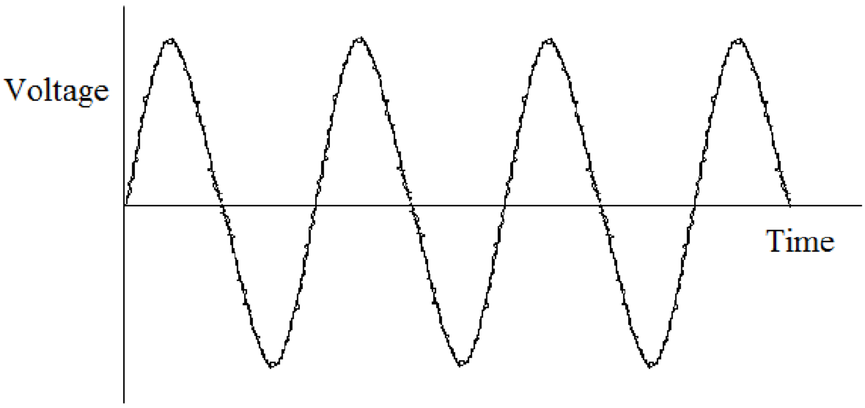

Fig.2.4 Distorted voltage waveform

2.4.5 Transients:

Transients results in oscillatory response of electrical circuit. These are the momentary changes in electrical signals for short duration of time. The cause can be external, internal or both.

It can be further categorized as:

1. **Impulsive transient:**

   It is an unexpected, frequency change in the steady state value of electrical signals, and the change is unidirectional either positive or negative. This duration exist between 5μs to 50ms. They are specified by their rise & decay time and spectral content.

2. **Oscillatory transient:**

   It is an unexpected frequency change in the steady state value of electrical signals, and the change is bidirectional i.e. both positive and negative polarity. This duration exist for less than50ns. Oscillatory transient is specified by the magnitude, duration and spectral content.

Transients are produced due to sudden switching on/off of load, loose connection and lightning stroke. This may result in overheating of motors and reduces the overall performance and shorten the lifetime of equipment.

2.5 Summary:

This chapter gives an overview of various PQ problems, causes and its consequences. This problem has to be identified and preventive measure should be taken to avoid severe problem in power system network. In this, focus is made on problem that mostly affects the end consumers i.e. voltage sags and swell. The following chapter gives an overview of current technique used for identifying such PQ problems. Among which, custom power device like DVR proves to be one of the most convincing and low-cost solution.

CHAPTER 3

STUDY OF DYNAMIC VOLTAGE RESTORER (DVR)

3.1 Introduction

3.2 Dynamic Voltage Restorer (DVR)

3.3 Basic structure and principle of DVR

3.4 Voltage injected by DVR

3.5 DVR control algorithm

3.1 <u>Introduction</u>:

Now a day's electrical equipment are more sensitive to PQ problems. Voltage sag/swell are one of considerable problem that our power system network is facing today. Without proper mitigation, such problem can cause severe problem and may result in failure of equipment. Modern development in custom devices can solve such problem. DVR is one of the effective solutions for compensation voltage sag/swell. This chapter gives an overview of DVR, its basic structure and operating principle.

3.2 <u>Dynamic Voltage Restorer</u>:

A DVR is a series connected custom device that injects the appropriate/desired voltage to the load bus in order to maintain the voltage profile. However, in standard condition it is in stand-by mode. The compensating voltage is injected by three single phase transformers whose property can be controlled. These voltages are in synchronism with the load voltage. DVR has three mode of operation:

3.2.1 <u>Protection mode</u>:

In order to isolate DVR from the system during overload current caused by short circuit or large inrush current, bypass switches are provided. The current is supplied to the system using other path.

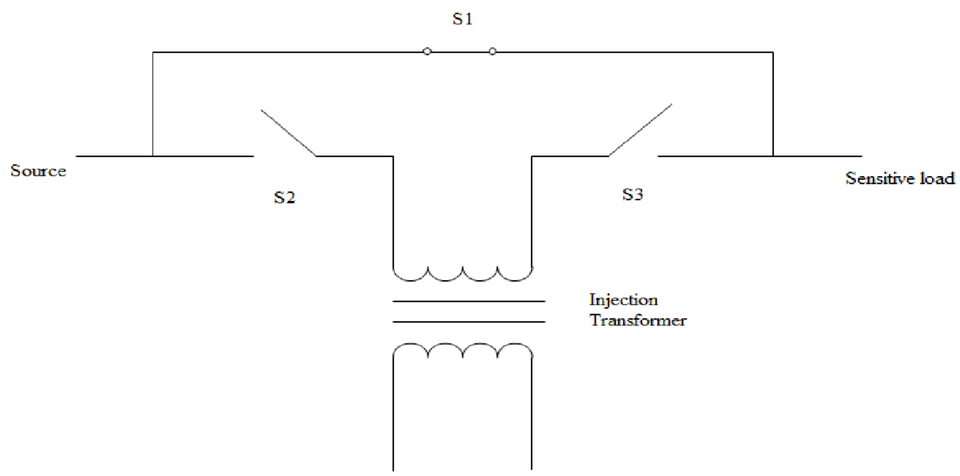

Fig.3.1: Protection mode

3.2.2 <u>Standby mode</u>:

In this mode, Low Voltage winding of injection transformer is shorted. No switching operation occurs in this mode.

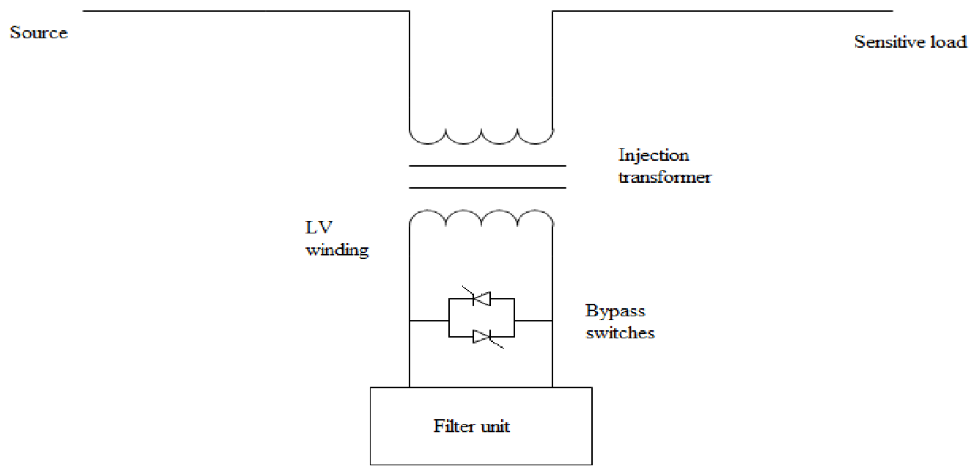

Fig.3.2: Standby mode

3.2.3 <u>Injection mode</u>:

In this mode, DVR injects the compensating voltage through injection transformer.

DVR in injection mode is carried out in following steps:

1. To find any voltage unbalance in the distribution network. This can be done by comparing the terminal voltage with load reference voltage. The difference is the desired voltage.
2. To initiate switching signals for Voltage Source Inverter (VSI), to track the desired voltage generated above by using satisfactory switching techniques such as SVPWM.
3. To filter harmonics by using passive filter, present in injected voltages.
4. To inject the filtered voltage using single phase transformers either connected in series with the load bus.

3.3 Basic structure and principle:

DVR is series connected compensating devices that restore/maintain the voltage profile at the sensitive loads under voltage unbalance. It is usually connected in the distribution network between Common Point of Coupling (PCC) and load. Fig.3.3 shows the location of DVR in power system network. The disturbance in the system is detected by control scheme used which generates the triggering pulses for VSI. Passive filters are used to filter out the harmonic content of injected voltage. DVR injects the filtered output voltage through injection transformer.

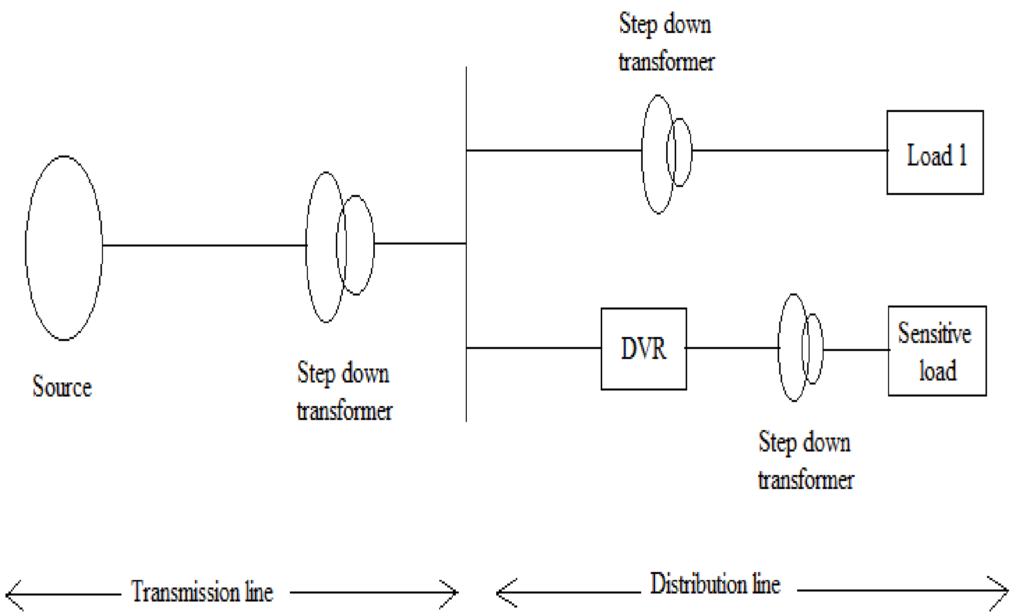

Fig.3.3: Location of DVR

The basic structure of DVR shown in fig.3.4 consists of following blocks:

1. VSI
2. Injection transformer
3. Passive filter
4. Energy storage unit
5. Control circuit

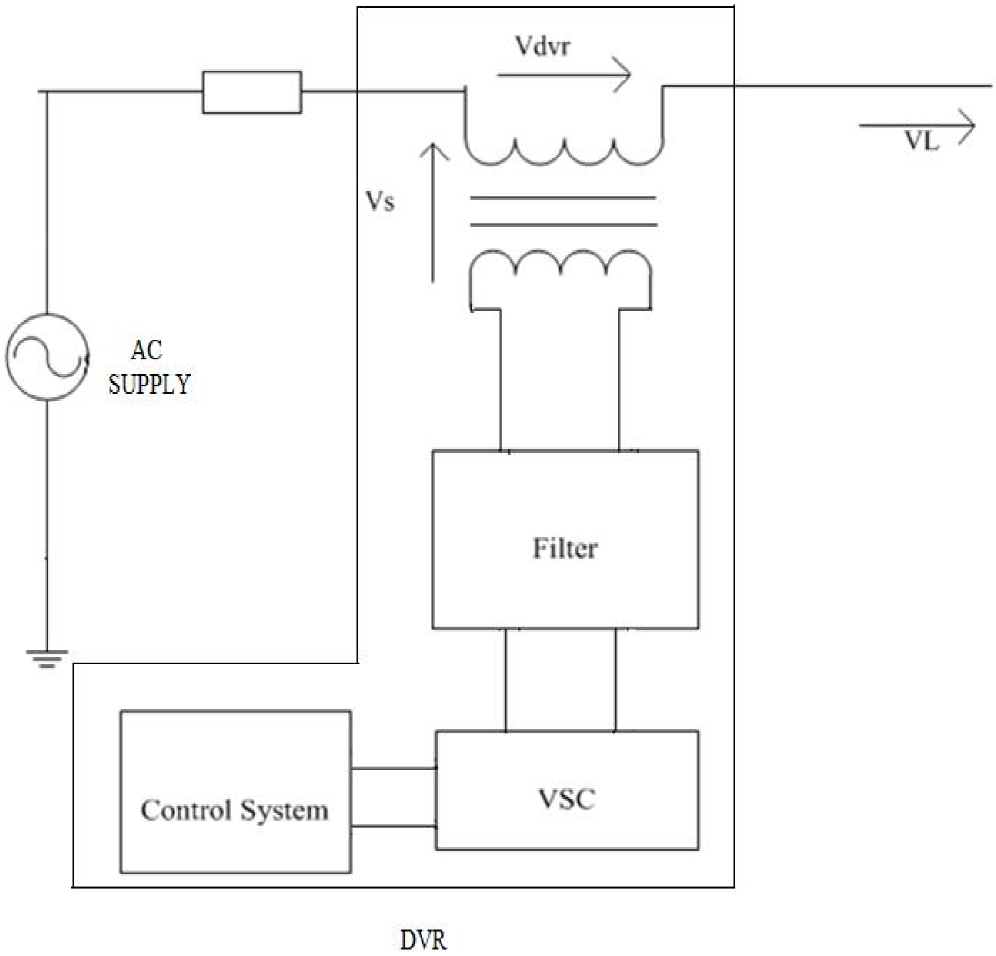

Fig3.4: Basic structure of DVR

➢ **Voltage Source Inverter (VSI):**

VSI converts fixed supply voltage stored into variable supply voltage. The converted voltage is boosted through the transformer. The rating is usually low voltage and high current since step up injection transformer is used. The output voltage of VSI should be:

i. Balanced and pure sinusoidal
ii. Same phase sequence as that of system
iii. Desired magnitude
iv. For particular time duration
v. Should be instantaneous

- **<u>Voltage injection transformer</u>:**

The AC voltage supplied by VSI is stepped up by using injection transformer to the desired voltage level. The winding connection of injection transformer depends on step down transformer connected in distribution line. It is either connected in star/open star winding or delta/open star winding. The former connection allows injection of zero sequence components as well whereas the latter connection does not allow it. Here three phase single transformer is used. The amount of voltage sag/swell compensated by DVR depends upon the rating of injection transformer and inverter.

- **<u>Passive filter</u>:**

It filters out the harmonics present in the output of the VSI. It can be kept either at the inverter side or at the HV side of the transformer. If filter is placed at the inverter side, switching harmonics are prohibited to enter the injection transformer thereby reduces rating and voltage stress on it. If the filter is placed at HV side of injection transformer, harmonics can enter into HV side hence rating of transformer increases.

- **<u>Energy storage unit</u>:**

During compensation, this unit provide the required real power to generate compensating voltage. Energy storage devices are lead acid batteries, flywheels, dc capacitors and super capacitors. Its capacity has great effect on compensation capability of DVR. The system with large disturbance requires real power compensation. DC to AC conversion required for batteries whereas AC to AC conversion required for flywheels.

- **<u>Control circuit</u>:**

Control circuit steadily observe the system. Its function is to detect any disturbance in the system done by comparing the supply voltage with reference voltage and generate the switching command signals for VSI in order to generate the compensating voltage by DVR.

3.4 <u>Calculation of Voltage injected by DVR</u>:

In fig.(3.5), the left side circuit of the DVR represents the equivalent thevenin circuit of the electrical network. When voltage unbalance occurs, DVR injects the desired voltage through injection transformer to maintain constant voltage profile. Z_{th} is the equivalent system impedance whose value depends upon the fault type.

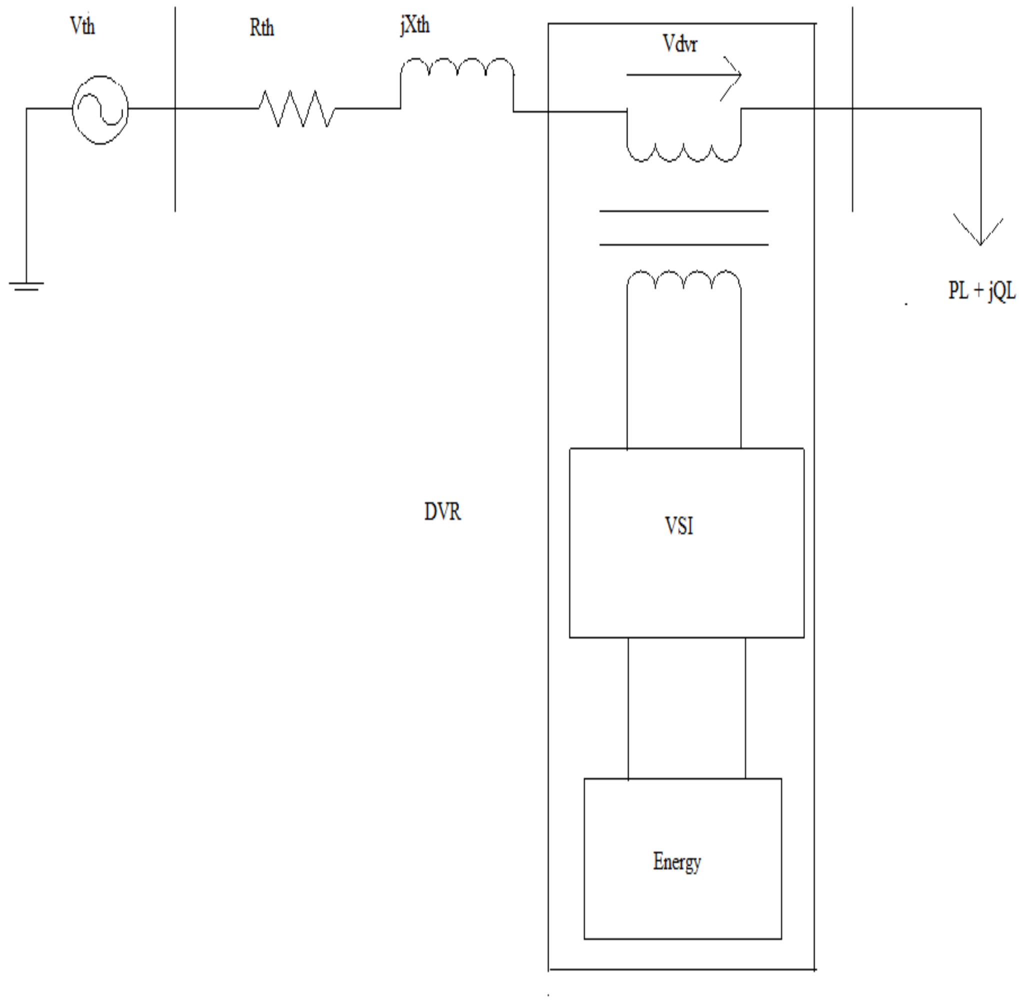

Fig.3.5: Schematic diagram of a DVR

As per the diagram shown in fig.(3.5):

Applying KVL,

$$V_{th} - Z_{th} I_L + V_{DVR} = V_L \tag{3.1}$$

$$V_{DVR} + V_{th} = V_L + Z_{th} I_L \tag{3.2}$$

The series voltage injected by DVR can be given as

$$V_{DVR} = V_L + Z_{th} I_L - V_{th} \tag{3.3}$$

Where, V_{th} = equivalent thevenin voltage of the system

V_L= load voltage

Z_{th} = equivalent thevenin impedance of the system

I_L= Load current and

$$I_L = \left[\frac{P_L + Q_L}{V_L}\right]^* \tag{3.4}$$

Taking V_L as reference, equation (3) can be rephrase as

$$V_{DVR}\angle\alpha = V_L\angle 0^0 + Z_{th} I_L \angle(\beta - \phi) - V_{th}\angle\delta \tag{3.5}$$

Where, α = angle of V_{DVR}

β = angle of system impedance Z_{th}

δ = angle of system impedance V_{th}

Φ = Load pf angle and

$$\phi = \tan^{-1}\left(\frac{Q_L}{P_L}\right) \tag{3.6}$$

The complex power injected by DVR is

$$S_{DVR} = V_{DVR} I_L^* \tag{3.7}$$

3.5 DVR control scheme:

The main objective is to maintain voltage profile on the load bus where sensitive load is connected. Here only active power is measured. The switching pulse generated for VSI is based on SVPWM. It is a simple method and better than other PWM techniques. Normally, three phase inverters use SPWM technique. However, problem like large noise peak at carrier frequency are present in such technique. Hence, SVPWM has an advantage over such technique such as better dc utilisation and easy implementation with digital signal processor. In this way, SVPWM is used as a control method for DVR.

The proposed control technique for DVR is shown in fig.3.6. The Phase Locked Loop (PLL) circuit used here is used to generate a unit sinusoidal wave which is in phase with main supply voltage.

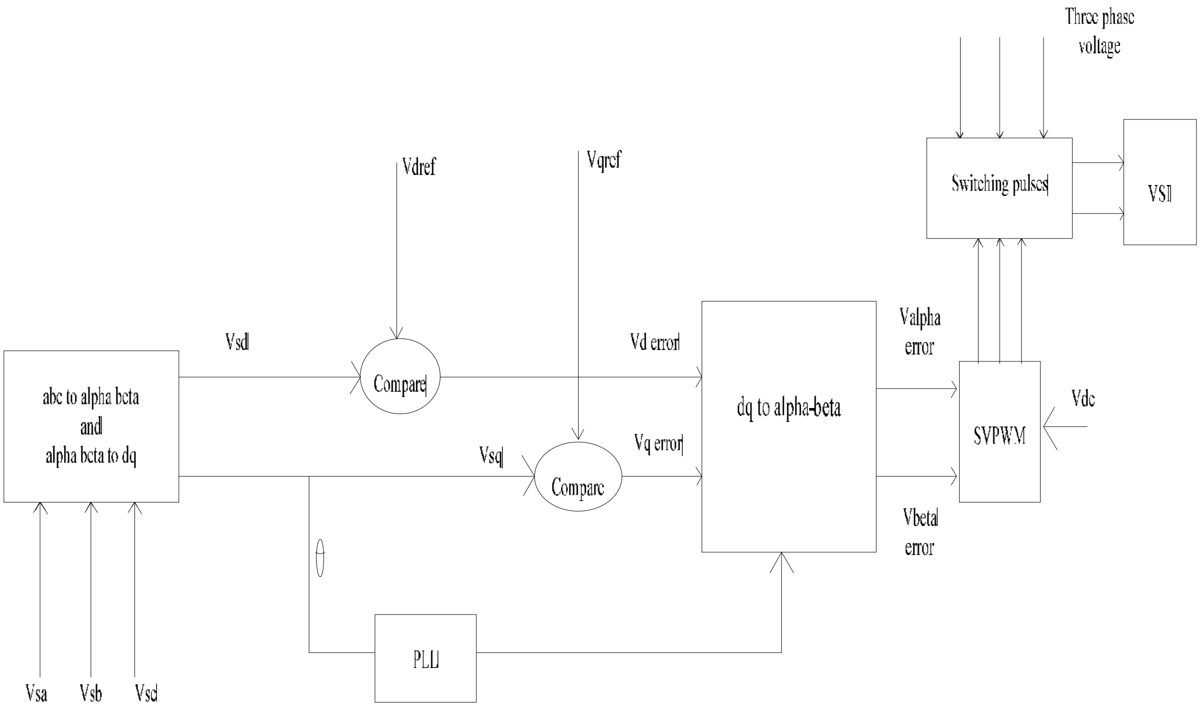

Fig.3.6: Control scheme for DVR

Block 1 converts three phase voltage into α-β coordinates given in equation (3.8) and α-β coordinates transformed into d-q plane given in equation (3.9). The d-q coordinates are compared with the reference signals. The d-q error generated is converted back to α-β coordinates and given to SVPWM generator to generate switching signals for VSI.

Transformation of three phase signal into α-β coordinates:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{3.8}$$

Transformation of α-β coordinates into d-q plane:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \tag{3.9}$$

Space vector modulation is an advanced PWM technique and better than other PWM techniques. It has find wide application in present years. SVPWM effectively generates six PWM pulses for a two level inverter. Typical circuit model of three phases VSI is shown in fig.3.7.

The two level VSI consist of six power electronic switches S_1 to S_6, whose gates are control by switching variables to control the inverter output. When an upper switch is on then the corresponding lower transistor is off. In this way, the states of the power electronic switches can be controlled by using different switching pattern for switching variables and hence the inverter output can be controlled.

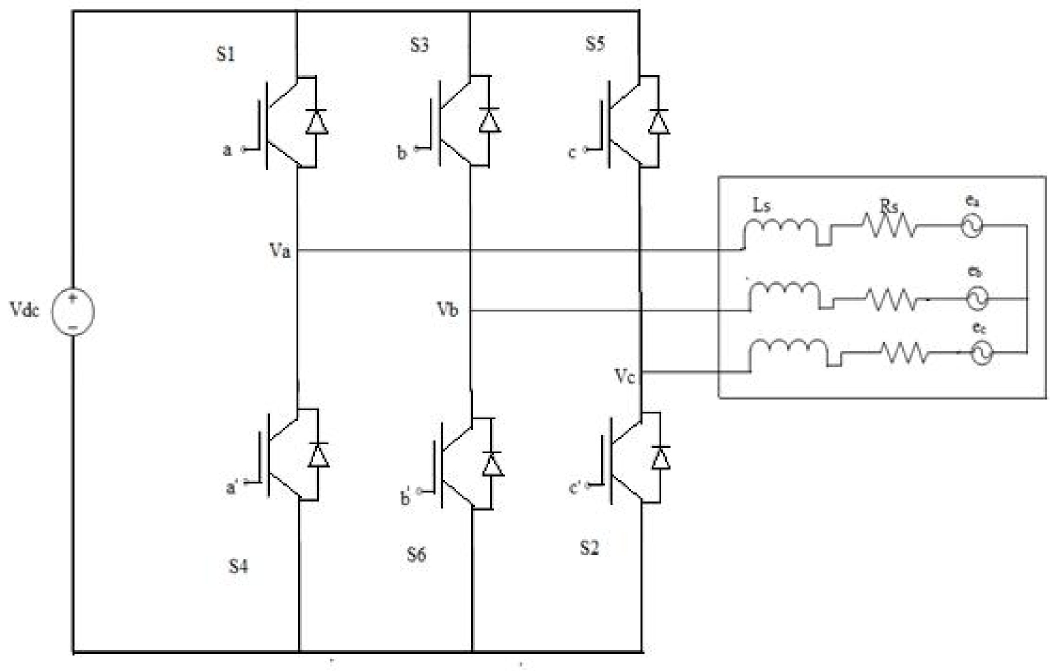

Fig.3.7: Three phase voltage source inverter

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Switching variables and line voltages can be related as:

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = V_{dc} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{3.10}$$

Switching variables and phase voltages can be related as:

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{V_{dc}}{3} \begin{bmatrix} 2 & -1 & 1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{3.11}$$

Eight possible switching states can be made from the upper switches. The states of lower switches are opposite to that of upper switches. The eight possible switching vectors are listed in the table 3.1.

Table 3.1: Switching state vectors

State(abc)	Vector	Magnitude	Angle
000	V_0	0	0
100	V_1	2/3	0
110	V_2	2/3	60
010	V_3	2/3	120
011	V_4	2/3	180
001	V_5	2/3	240
101	V_6	2/3	300
111	V_7	0	0

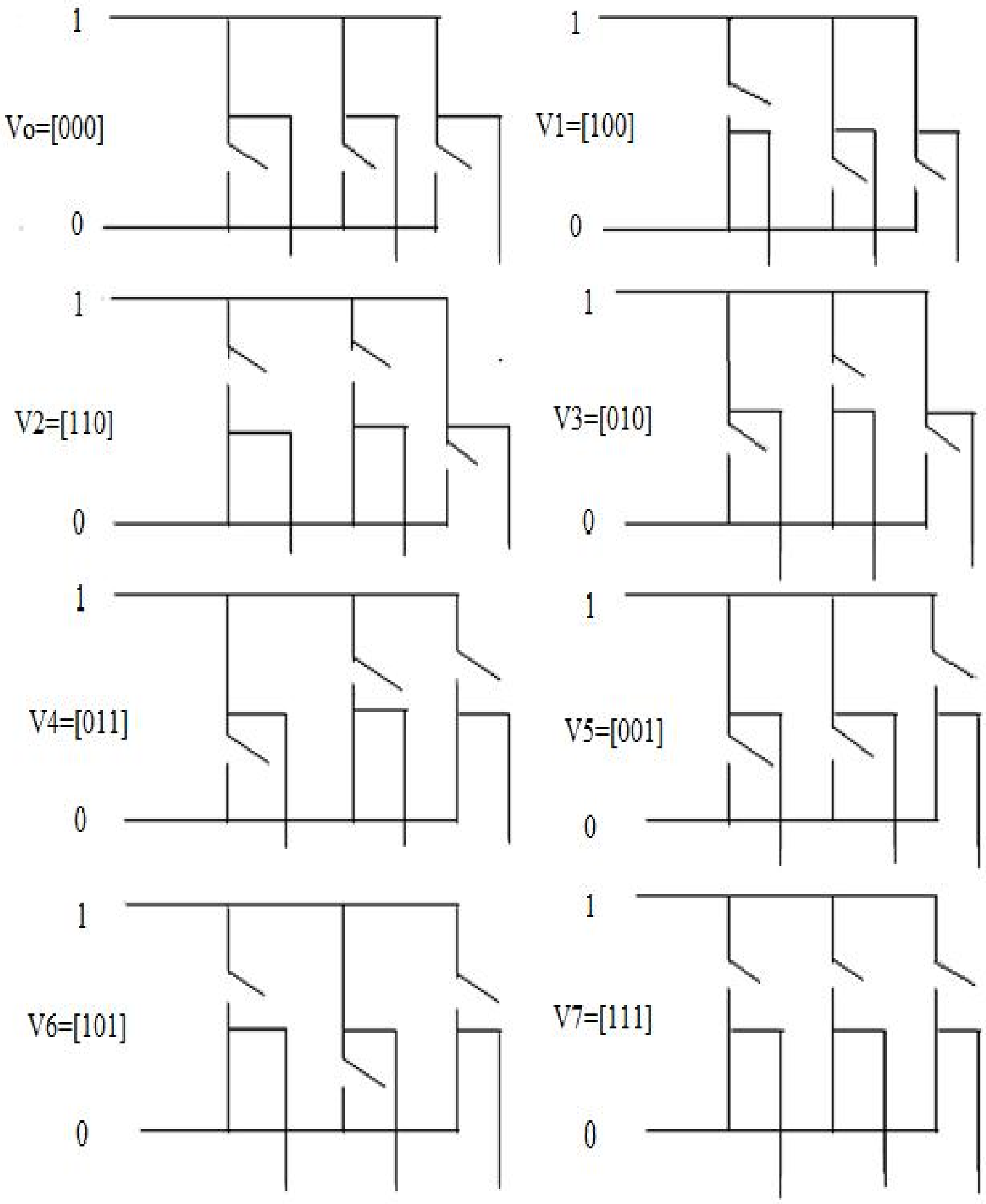


Fig.3.8: The eight inverter voltage vector

To implement SVPWM, three phase voltages are transformed into stationary dq reference frame. In phasor diagram, the three phase voltages are represented into orthogonal coordinates.

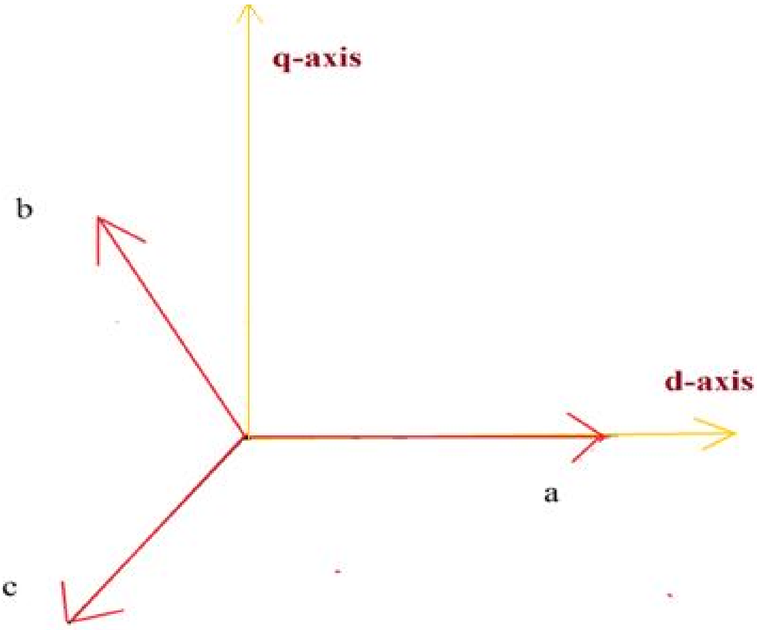


Fig.3.9: abc to stationary dq reference frame

In fig.(3.9), the two reference frame can be related as:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{3.12}$$

The three phase voltage can be represented by a reference voltage vector (V_{ref}), which rotates in space at an angular speed ω. The task is to evaluate the reference vector by using the eight possible switching pattern. Out of eight vectors, six are non-zero vectors (V_1 to V_6) and two are null vectors (V_0 and V_7). The angle subtended by any two adjoining non-zero vectors is 60^0. V_0 and V_7 exist at the origin and provide no output.

It can be easily implemented by generating average inverter output for small time duration, T equal to the reference voltage vector for the same duration.

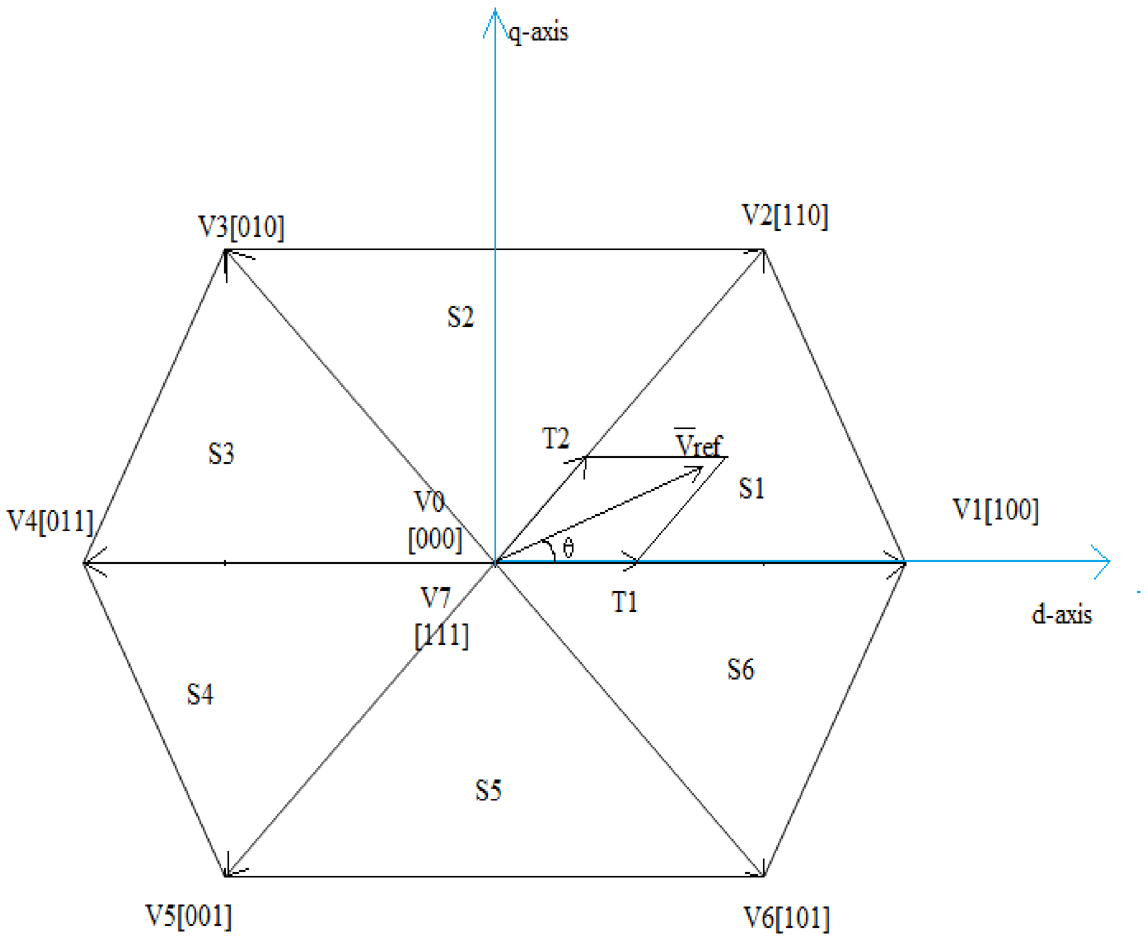


Fig.3.10: Switching vectors and sectors

SVPWM can be executed by:

i. To evaluate reference voltage (V_{ref}) and angle (α).
ii. To evaluate the time duration T_1, T_2 and T_0.
iii. To evaluate the switching time of the transistors.

➢ **Step 1: To evaluate the V_{ref} and angle (α):**

$$V_d = V_{an} - \frac{1}{2}V_{bn} - \frac{1}{2}V_{cn} \tag{3.13}$$

$$V_q = V_{an} + \frac{\sqrt{3}}{2}V_{bn} - \frac{\sqrt{3}}{2}V_{cn} \tag{3.14}$$

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} \tag{3.15}$$

$$V_\alpha = V_d cos\theta - V_q sin\theta \tag{3.16}$$

$$V_\beta = V_d sin\theta + V_q cos\theta \tag{3.17}$$

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{bmatrix} \tag{3.18}$$

$$|V_{ref}| = \sqrt{V_\alpha^2 + V_\beta^2} \tag{3.19}$$

$$\alpha = \tan^{-1}\left(\frac{V_\beta}{V_\alpha}\right) = \omega t \tag{3.20}$$

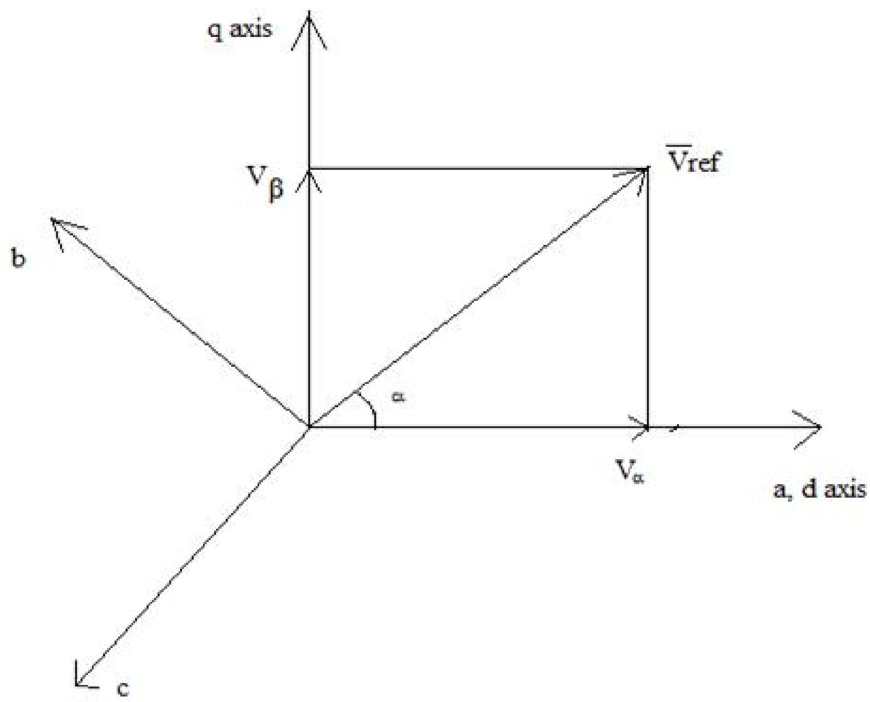


Fig.3.11: Voltage space vector

- **Step 2: To evaluate T_1, T_2 and T_0:**
  - Switching time duration in sector 1:

$$\int_0^{T_z} \overline{V_{ref}} = \int_0^{T_1} \overline{V_1}\, dt + \int_{T_1}^{T_1+T_2} \overline{V_2}\, dt + \int_{T_1+T_2}^{T_z} \overline{V_0} \tag{3.21}$$

$$\therefore T_z.\overline{V_{ref}} = (T_1.\overline{V_1} + T_2.\overline{V_2}) \tag{3.22}$$

$$T_z.\left|\overline{V_{ref}}\right|.\begin{bmatrix} cos(\alpha) \\ \sin\ (\alpha) \end{bmatrix} = T_1.\frac{2}{3}.V_{dc}.\begin{bmatrix} 1 \\ 0 \end{bmatrix} + T_2.\frac{2}{3}.V_{dc}.\begin{bmatrix} \cos\ (\pi/3) \\ \sin\ (\pi/3) \end{bmatrix} \tag{3.23}$$

(where, $0 \leq \alpha \leq 60^0$)

$$\therefore T_1 = T_z.a.\frac{\sin\ (^{\pi}/_{3}-\alpha)}{\sin\ (^{\pi}/_{3})} \tag{3.24}$$

$$\therefore T_2 = T_z.a.\frac{\sin\ (\alpha)}{\sin\ (^{\pi}/_{3})} \tag{3.25}$$

$$\therefore T_0 = T_z - (T_1 + T_2) \tag{3.26}$$

$$(where, T_z = \frac{1}{f_z}\ and\ a = \frac{\left|\overline{V_{ref}}\right|}{\frac{2}{3}V_{dc}})$$

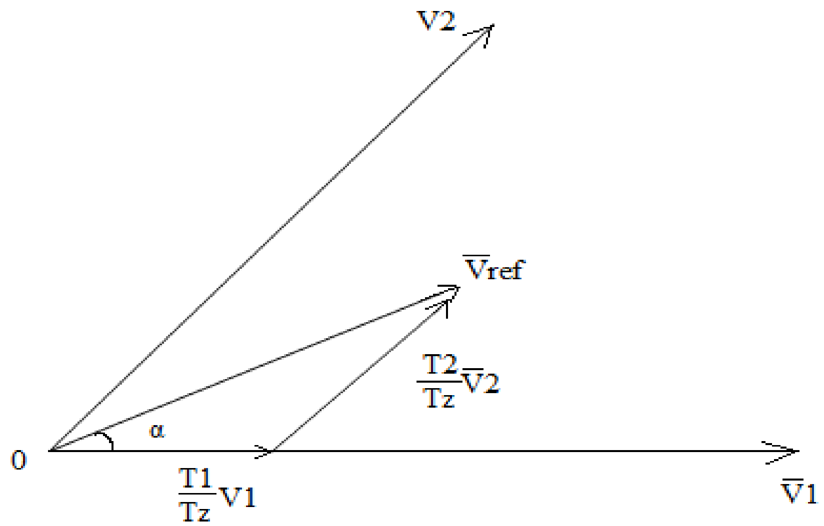


Fig.3.12: Reference voltage vector

- Switching time duration of any sector:

$$T_1 = \frac{\sqrt{3}.T_Z.|\overline{V_{ref}}|}{V_{dc}}\left(\sin\left(\frac{\pi}{3} - \alpha + \frac{n-1}{3}\pi\right)\right)$$

$$= \frac{\sqrt{3}.T_Z.|\overline{V_{ref}}|}{V_{dc}}\left(\sin\left(\frac{n}{3}\pi - \alpha\right)\right)$$

$$= \frac{\sqrt{3}.T_Z.|\overline{V_{ref}}|}{V_{dc}}\left(\sin\frac{n}{3}\pi\cos\alpha - \cos\frac{n}{3}\pi\sin\alpha\right) \tag{3.27}$$

$$T_2 = \frac{\sqrt{3}.T_Z.|\overline{V_{ref}}|}{V_{dc}}\left(\sin\left(\alpha - \frac{n-1}{3}\pi\right)\right)$$

$$= \frac{\sqrt{3}.T_Z.|\overline{V_{ref}}|}{V_{dc}}\left(-\cos\alpha.\sin\frac{n-1}{3}\pi + \sin\alpha.\cos\frac{n-1}{3}\pi\right) \tag{3.28}$$

$$\therefore T_0 = T_z - T_1 - T_2 \tag{3.29}$$

$(where\ n = no.of\ sector\ i.e.from\ 1\ to\ 6)$

$(0 \leq \alpha \leq 60^0)$

- **Step 3: To evaluate switching time:**

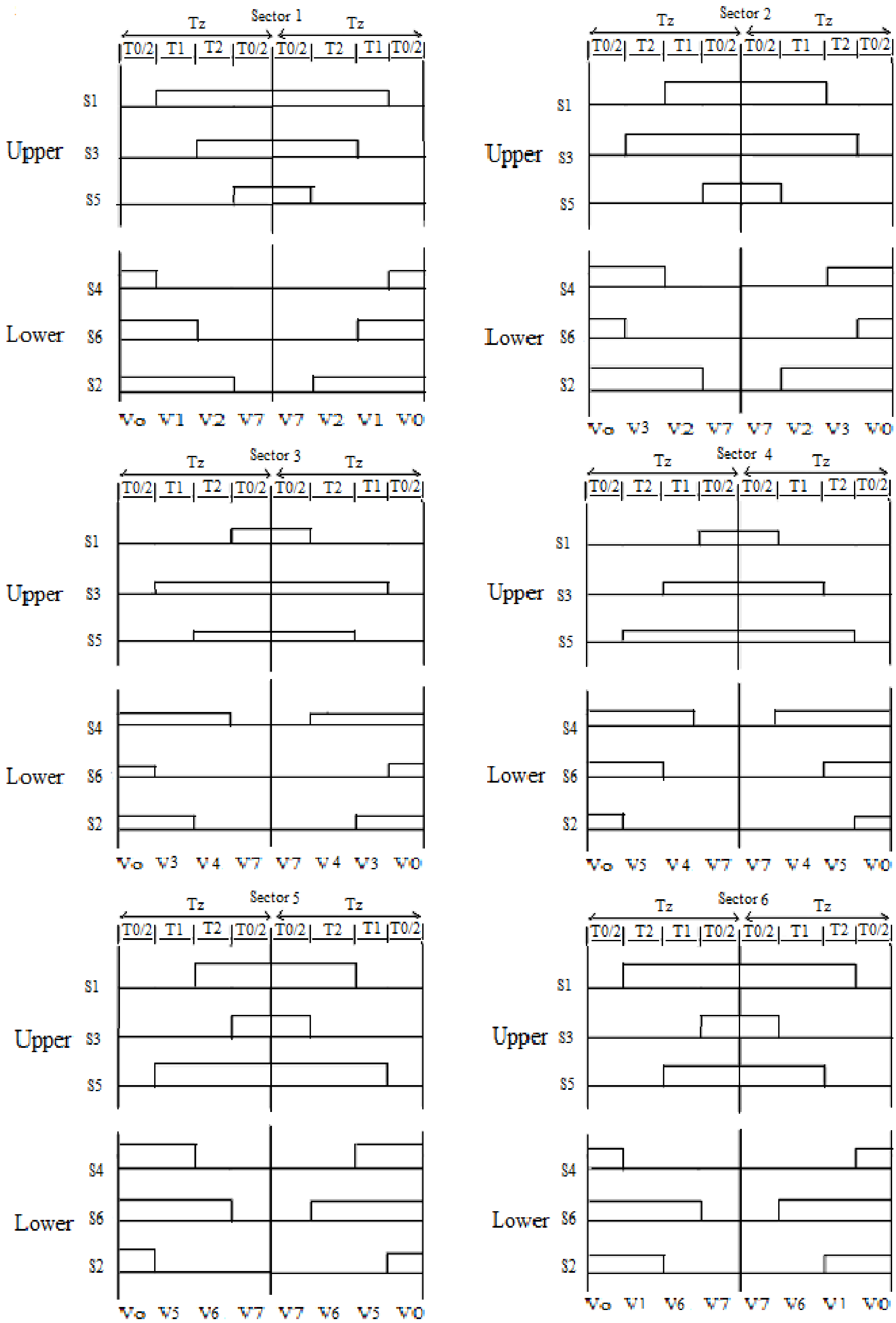


Fig.3.13: Switching pattern of each sector

Table 3.2: Switching sequence of the sectors

Sector	Upper switches (S_1, S_3 and S_5)	Lower switches (S_4, S_6 and S_2)
1	$S_1=T_1+T_2+T_0/2$ $S_3=T_2+T_0/2$ $S_5=T_0/2$	$S_4=T_0/2$ $S_6=T_1+T_0/2$ $S_2=T_1+T_2+T_0/2$
2	$S_1= T_1+T_0/2$ $S_3= T_1+T_2+T_0/2$ $S_5=T_0/2$	$S_4=T_2+T_0/2$ $S_6=T_0/2$ $S_2=T_1+T_2+T_0/2$
3	$S_1=T_0/2$ $S_3=T_1+T_2+T_0/2$ $S_5=T_2+T_0/2$	$S_4=T_1+T_2+T_0/2$ $S_6=T_0/2$ $S_2=T_1+T_0/2$
4	$S_1=T_0/2$ $S_3= T_1+T_0/2$ $S_5=T_1+T_2+T_0/2$	$S_4=T_1+T_2+T_0/2$ $S_6=T_2+T_0/2$ $S_2=T_0/2$
5	$S_1=T_2+T_0/2$ $S_3=T_0/2$ $S_5=T_1+T_2+T_0/2$	$S_4=T_1+T_0/2$ $S_6=T_1+T_2+T_0/2$ $S_2=T_0/2$
6	$S_1=T_1+T_2+T_0/2$ $S_3=T_0/2$ $S_5=T_1+T_0/2$	$S_4=T_0/2$ $S_6=T_1+T_2+T_0/2$ $S_2=T_2+T_0/2$

Chapter 4

SIMULATION RESULTS AND DISCUSSION

The system parameters used while simulating DVR for compensating voltage disturbances is shown in table 4.1.

Table 4.1 Specification of parameters

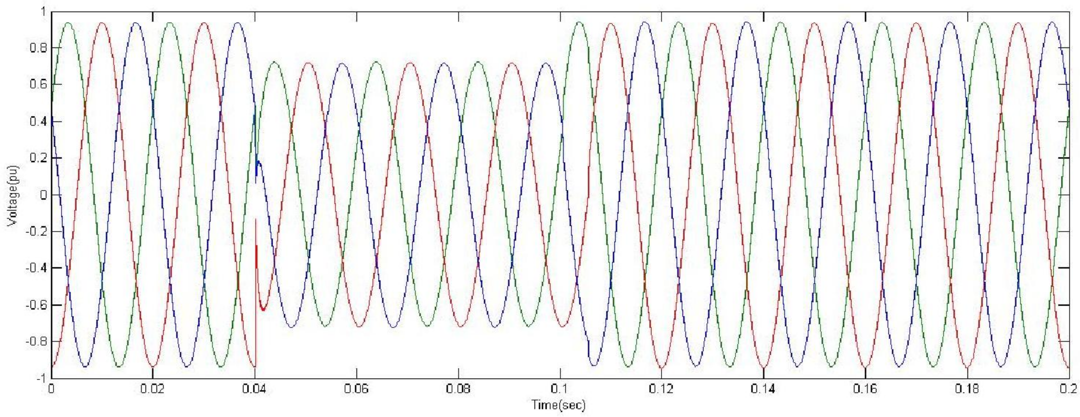
Supply voltage	200 volts/ phase
Line resistance	0.1ohm
Line inductance	0.5mH
DC supply	120V
DC capacitor	2200µF
Filter	L_F=7mH and C_F=100µF
Load	R_L=40ohm and L_L=60mH
Supply frequency	50Hz
Switching frequency	10kHz

Voltage dip occurs due to sudden disconnection of load or faults in the system whereas voltage swell occurs due to connection of capacitive load. Voltage unbalance occurs for certain duration in the system due to faults in the network. During this period voltage disturbance occurs at PCC (Point Of Coupling) and DVR operates to restore/maintain the voltage profile. Here all voltages are taken in per unit values, whenever disturbance occurs it can be observed that the magnitude voltage profile increases/decreases from its rated value. DVR operates and inject the desired voltage to compensate this voltage rise/dip. After compensation, there is slight disturbance at the start and end point of sag/swell occurs due to addition of compensating voltage during this period.

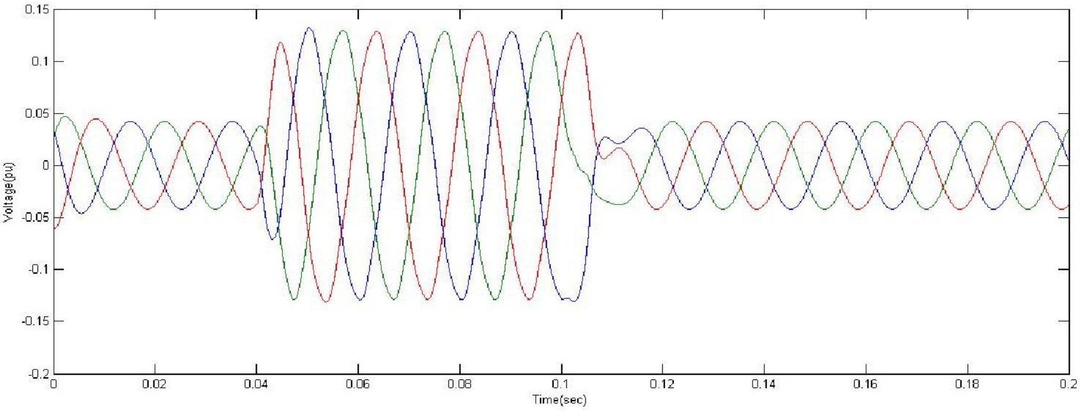
4.1 Voltage Sag Compensation:

4.1.1 Compensation of balanced voltage sag:

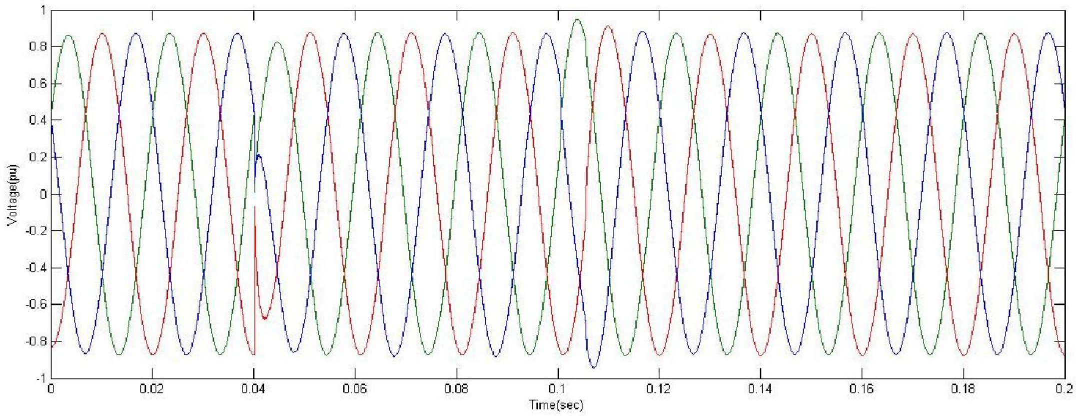
A three phase fault is generated in the system to create balanced voltage sag for time duration of 0.04s to 0.1s. The PCC voltage after the sag occurs for the duration of 0.06s is shown in fig.4.1 (a). The DVR respond to this disturbance and inject the compensating voltage. The compensated voltage is shown in fig.4.1 (b). After sag compensation, the load voltage regains its previous profile. The load voltage after compensation is shown in fig.4.1 (c).



(a): PCC voltage



(b): Compensating voltage

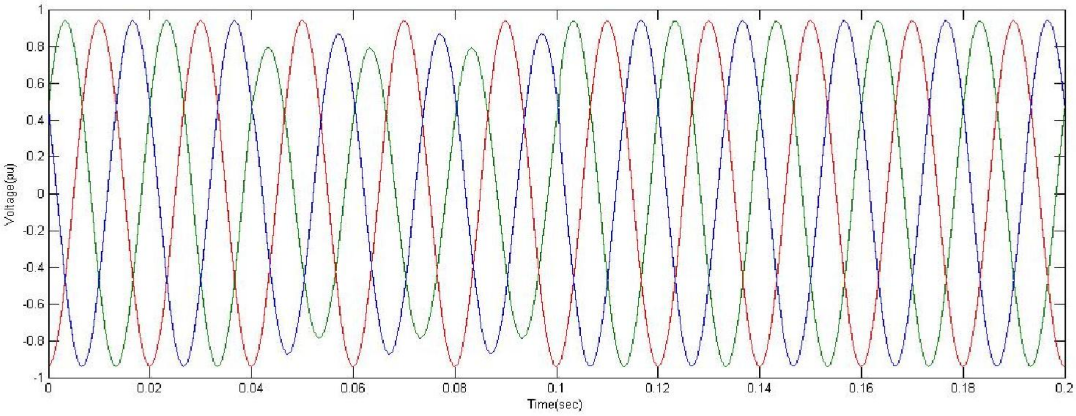


(c): Load voltage after compensation

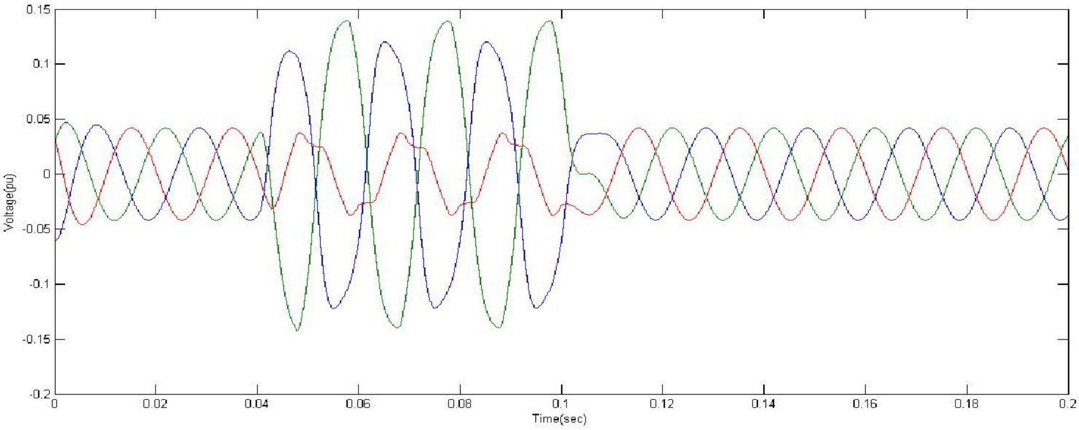
Fig.4.1: Simulation results for balanced voltage sag

4.1.2 <u>Compensation of unbalanced voltage sag</u>:

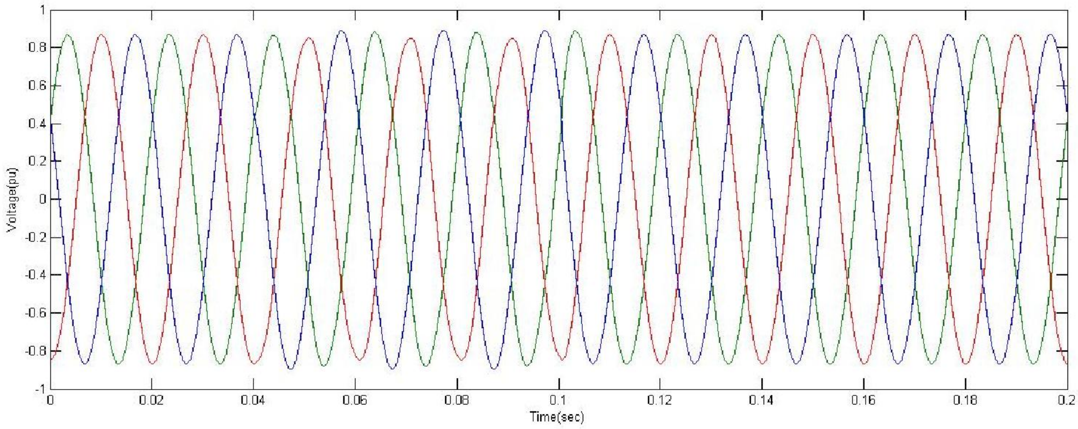
Unbalanced voltage sag occurs due to SLG fault in the network for time duration of 0.04s to 0.1s. The PCC voltage after the sag occurs for duration of 0.06s is shown in fig.4.2 (a). DVR injects the desired voltage for this duration. The compensating voltage injected by DVR is shown in fig.4.2 (b). After the successful operation of DVR and sag compensation, the compensated load voltage is shown in fig.4.2 (c).



(a): PCC voltage



(b): Compensating voltage



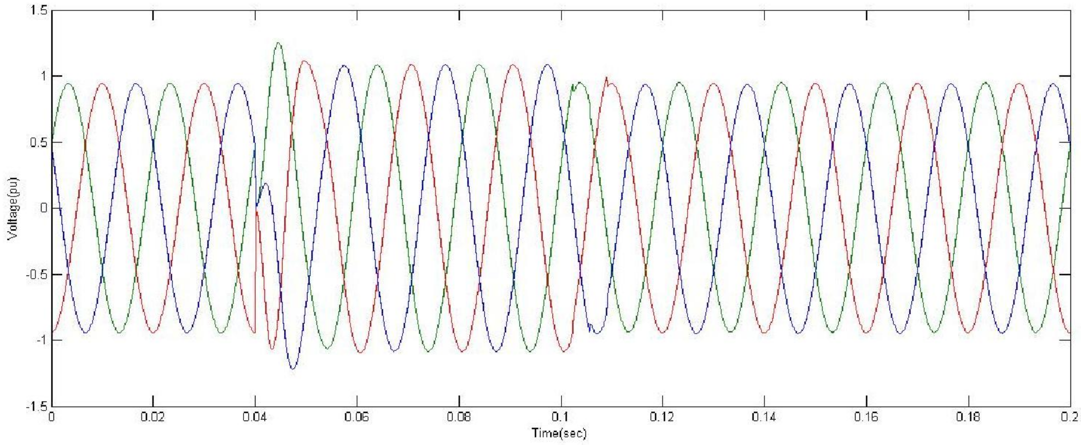
(c): Load voltage after compensation

Fig.4.2: Simulation results for unbalanced voltage sag

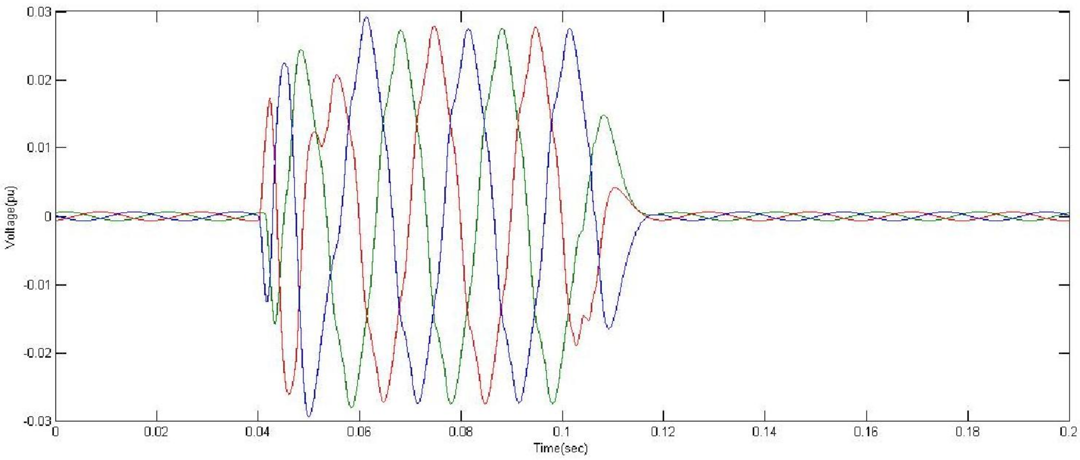
4.2 Voltage Swell compensation:

4.2.2 Compensation of balanced voltage swell:

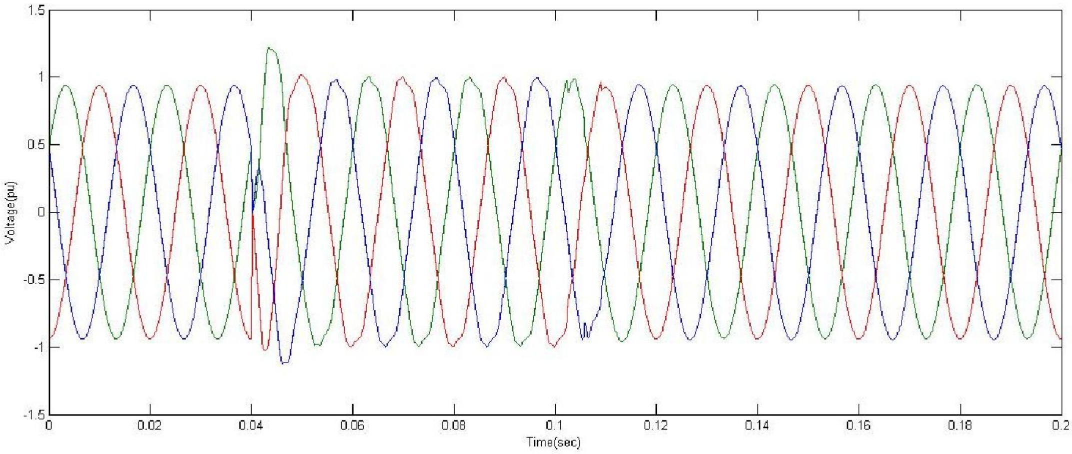
A three phase balanced voltage swell occurs by connecting a capacitive load in the network for time duration of 0.04s to 0.1s. The PCC voltage after the voltage unbalance for this duration is shown in fig.4.3 (a). The compensating voltage injected by DVR is shown in fig. 4.3 (b). After successful compensation, the compensated load voltage is shown in fig.4.3 (c).



(a): PCC voltage



(b): Compensating voltage

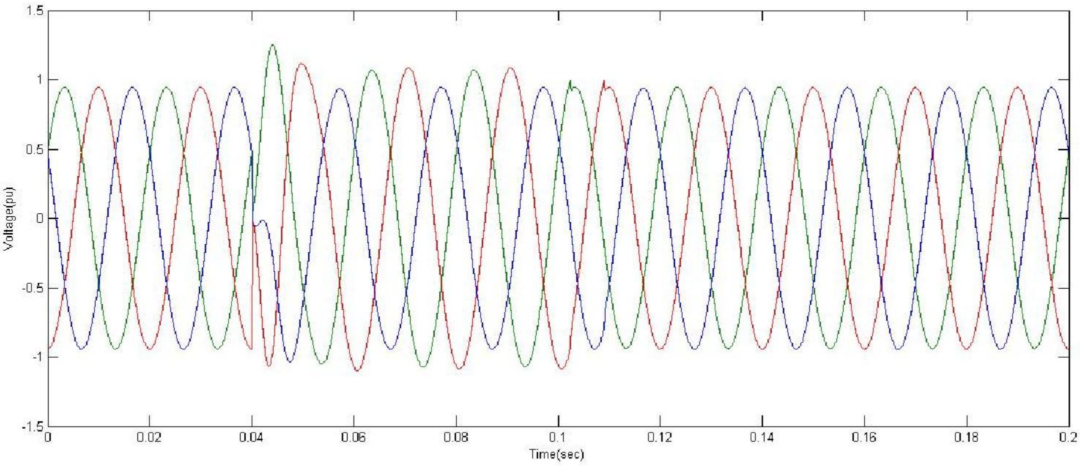


(c): Load voltage after compensation

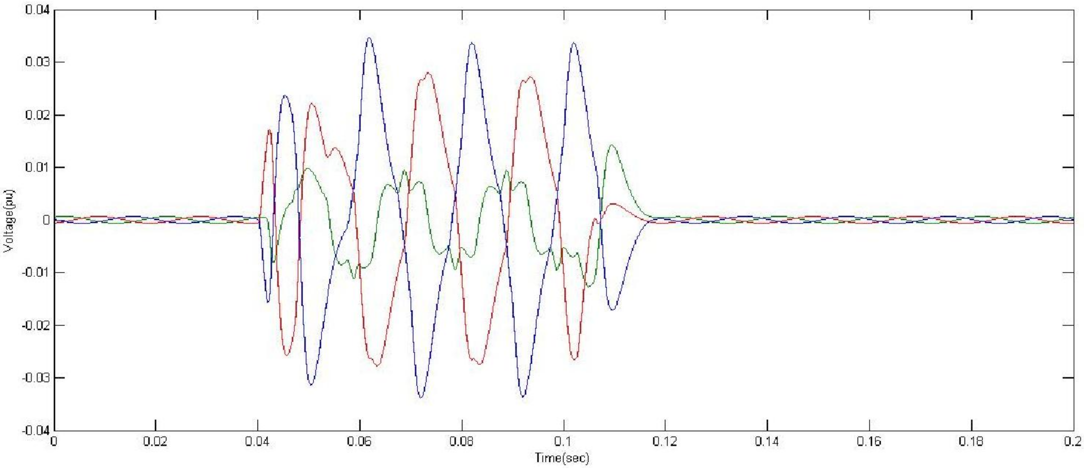
Fig.4.3: Simulation results for balanced voltage swell

4.2.3 <u>Compensation of unbalanced voltage swell</u>:

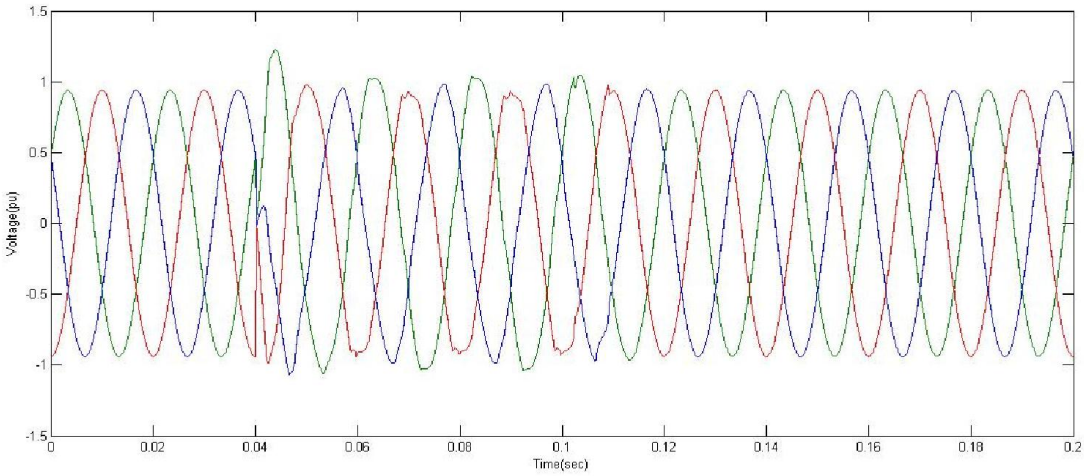
A unbalanced voltage swell occurs by generating a two phase swell in the network for duration of 0.04s to 0.6s. The PCC voltage for this duration is shown in fig.4.2 (d). The compensating voltage injected by DVR is shown in fig.4.2 (e). After successful compensation, the compensated load voltage is shown in fig.4.2 (f).



(a): PCC voltage



(b): Compensating voltage



(c): Load voltage after compensation

Fig.4.4: Simulation results for unbalanced voltage swell

4.3 Summary:

This chapter presents the simulation result for both balanced and unbalanced voltage sag and swell. It also provides an overview and behavioural study of the compensating device i.e. DVR for mitigating such voltage disturbances.

CHAPTER 5

CONCLUSION AND FUTURE SCOPE

5.1 Conclusion:

The demand for quality power has become a challenging issue for industrial area and consumers. Among them voltage unbalance is considered as the major affecting problem leads to degradation in performance of electrical equipments. FACTS devices used for compensation are the best method to overcome such problem. Among them DVR considered the most efficient and cost effective.

Voltage unbalances such as voltage sag/swell are considered here. Voltage unbalance under both balanced and unbalanced condition is considered and simulation results are shown. Modelling and compensating technique used by DVR for compensating such unbalance are also presented. The simulation result shows that DVR compensate sag/swell effectively and provide good voltage regulation. The performance of DVR is satisfactory.

5.2 Future scope:

1. Other power quality problem that occurs in power system network has to be compensated.
2. Fuzzy controller and PI controller can be used as a mitigation technique for DVR.

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